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A study of an electric method to excite and detect acoustic waves in solids

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A STUDY OF AN ELECTRIC METHOD TO
EXCITE AND DETECT ACOUSTIC WAVES IN SOLIDS

by

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A

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ABSTRACT

This experiment has demonstrated that it is possible to generate pulses of acoustic waves in an aluminum single crystal by the direct use of the tensile stress associated with an electric field at the surface of a conductor, and it is possible to detect these waves with a biased, capacitive pickup transducer.

ACKNOWLEDGMENTS

The author wishes to thank Dr. Charles E. McFarland for his advice and support, without which this work would not have been possible.

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I. INTRODUCTION

A. Discussion

There are many properties of solids which can be studied by the use of ultrasonics. Information concerning attenuation, scattering, and velocities of ultrasonic radiation in solids can be obtained by this technique. Prior to 1950, the use of ultrasound in studying these properties was not widely used. The methods were and still are vexed by difficulties such as pulse shaping and in bonding the transducers to the sample. There are several methods which can be used in coupling a mechanical disturbance, such as a pulsed or sinusoidal wave, to a sample.

(1) The piezoelectric method: Here a piezoelectric transducer is bonded to a sample and an electric field applied to the transducer. The transducer converts this signal to a mechanical wave which is then transmitted into the sample. Bonding and frequency limitations are a problem. Since the thickness and the resonant frequency of the transducer are inversely proportional, it can be seen that at higher frequencies the transducer becomes thin enough to become difficult to work with.

(2) The magnetostrictive method: In this method a rod of magnetic material bonded to a sample is subjected to an alternating magnetic field parallel to

its axis. Mechanical vibrations are generated which are transmitted to the sample. As a result of the inductance in an electromagnet, the back emf prohibits short duration pulsing of the magnetic field.

(3) The microwave method: When using the microwave method, a piezoelectric sample is placed in a tuned cavity where microwaves of the desired frequency are used to excite acoustic waves at the surface of the sample. The disadvantages are that the method is limited to piezoelectric samples, and that when different frequencies are desired, different cavities have to be used.

In this experiment an electric method was employed. Here the longitudinal modes in the sample were excited by an alternating electric field. A flat plate, or electrode, was fixed with its face parallel to, and a short distance from, the sample as shown in Fig. 1. More will be said concerning these particulars in a later section. The use of an electric field, both for producing and detecting acoustic vibrations, is one of the essential features of this method. With this method the absence of a piezoelectric transducer eliminates electromechanical resonance which appears when one uses the piezoelectric method. Another attractive feature of the electric method is that there is no direct contact between the sample and the electrode, so energy losses in the piezoelec-

Fig. 1

Position of the Electrode

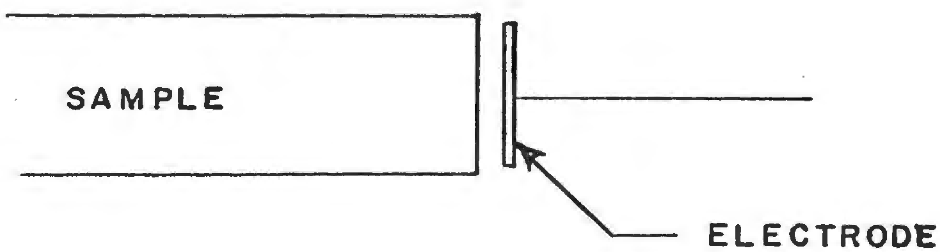

FIG. 1

tric crystal and its bond are eliminated.

B. Review

The use of ultrasound in solid state studies essentially started in 1947 when Mason, et. al.[1] measured the attenuation and scattering of high frequency sound waves in metals and glasses. In his experiment the sound pulses were generated by piezoelectric crystals attached to the sample with beeswax. Measurements were made in the frequency range from 2 to 15 megacycles, but the wax bond limited the band width of the transmitted pulse. For this reason long pulses were used, which approached steady state conditions. The electrical circuit used by Mason is shown in Fig. 2. This circuit is basically a reliable one, and is used now in some experiments.

In 1947, P. G. Bordoni used the continuous wave electrical method for research on elasticity. He claimed excellent results in the low megacycle range in that he was able to detect electrode vibrations as small as one angstrom.

In 1948, W. Roth[2] reported a method for measuring absorption of ultrasound in polycrystalline metals in the frequency range of 15 to 100 megacycles using the pulse-echo techniques. Here Roth used an X-cut quartz piezoelectric transducer. The transducer was acoustically loaded in a bath of distilled water. The acoustical energy from the transducer was transmitted through the water and into the

Fig. 2

Electrical Circuit Used by Mason

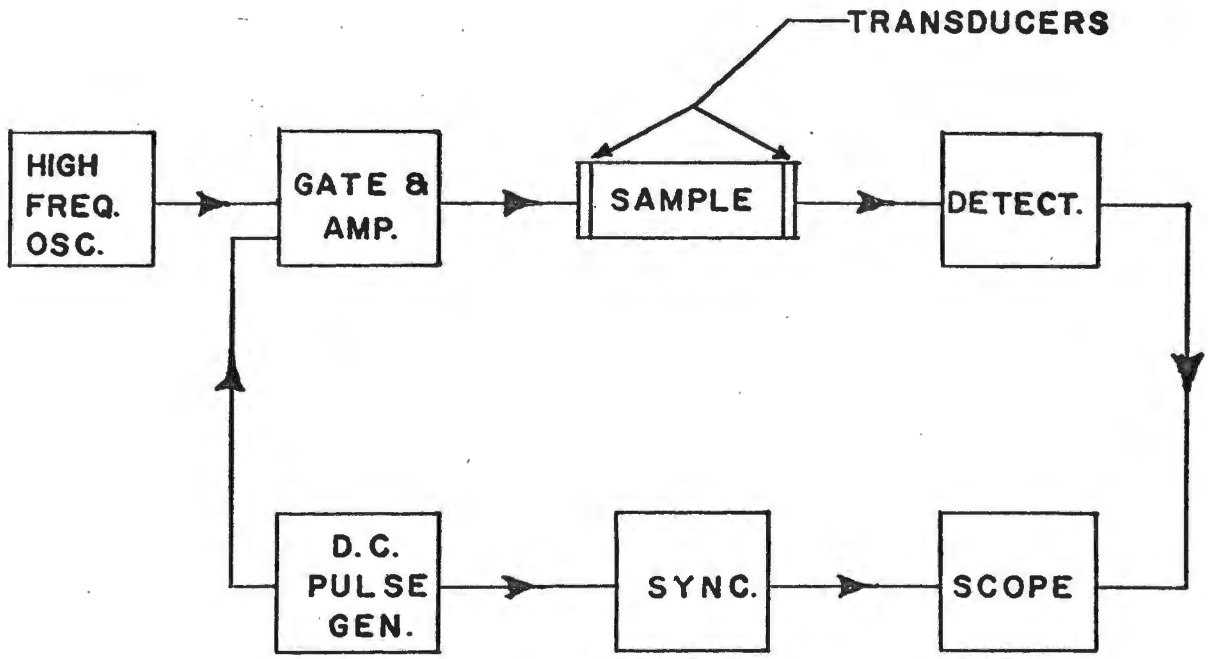
TRANSDUCERS
HIGH FREQ. OSC.
GATE & AMP.
SAMPLE
DETECT.
D.C. PULSE GEN.
SYNC.
SCOPE

FIG. 2

sample, through which it propagated. After being reflected from the second surface of the sample, the pulse returned through the water to the same transducer as that used for transmission. If transverse waves are necessary, the water buffer method cannot be used. Fig. 3 shows this experimental arrangement. The water loaded method limits the minimum pulse length that can be used, and cavitation in the water is also a problem.

In 1951, R. L. Roderick, et. al.[3] used the pulse technique to measure the ultrasonic attenuation in steel samples. The experiment was carried out using both the transducer and water bath methods. Frequencies here ranged from 5 to 50 megacycles. Fig. 4 shows the electrode arrangement with the crystal mounted directly on the specimen. The crystals used here were three 3/4 inch X-cut quartz; a 5 megacycle crystal operated at 5, 15, 25, 35, and 45 megacycles; a 10 megacycle crystal operated at 10, 30, and 50 megacycles; and a 20 megacycle crystal operated at its fundamental frequency.

In 1960, P. G. Bordoni[4] used the electrical method to investigate the elastic and anelastic behavior of metals at very low temperatures. Both in this work and in his work in 1947, continuous rather than pulsed waves were used. In this work the frequency used was 7 megacycles. Some of the characteristics of the experimental apparatus are listed in Table I.

Fig. 3

Water Loaded Method Used by Roth

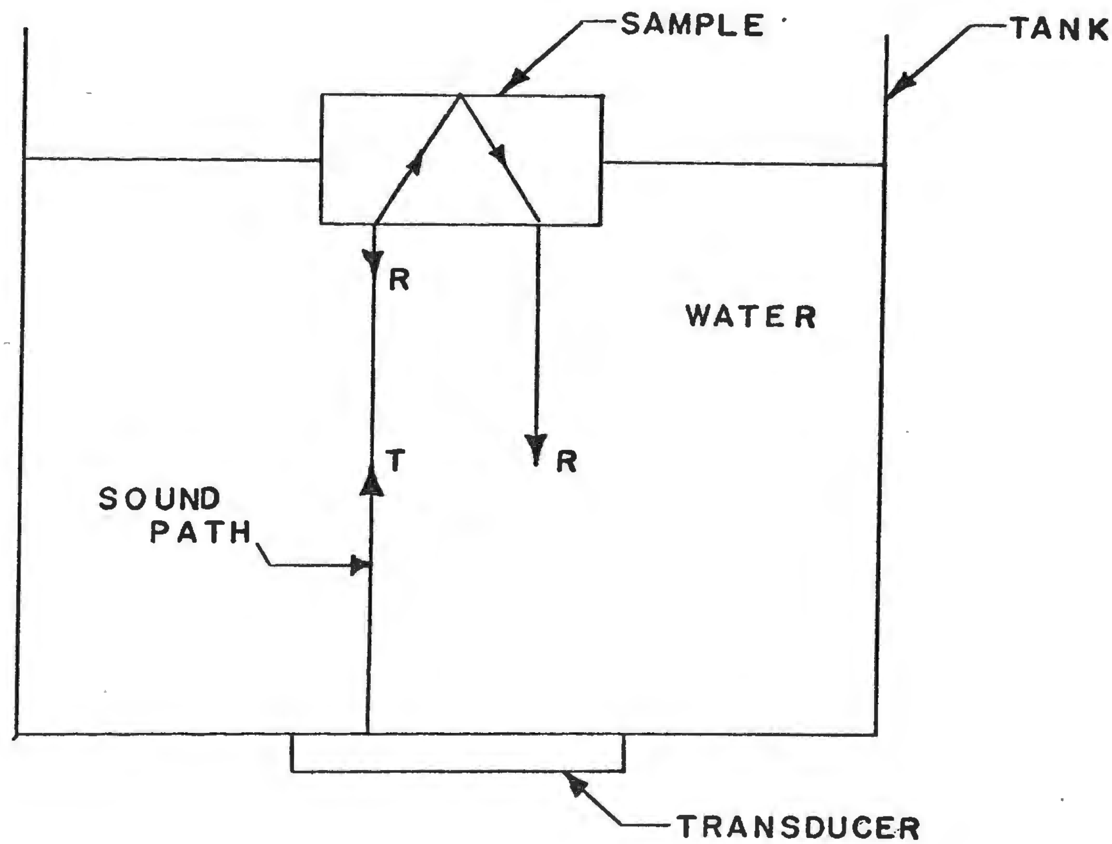

FIG. 3

Fig. 4

Piezoelectric Method Used by Roderick

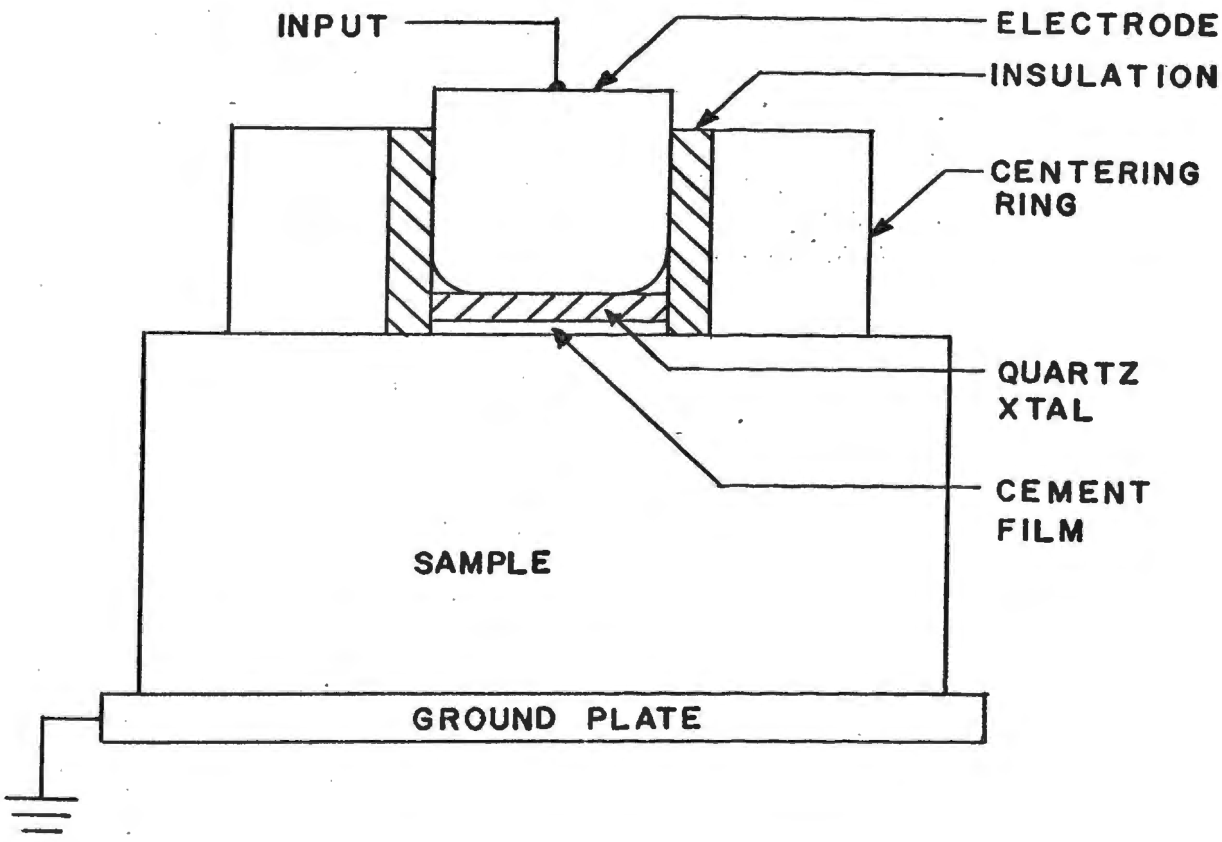
INPUT
ELECTRODE
INSULATION
CENTERING RING
QUARTZ XTAL
CEMENT FILM
SAMPLE
GROUND PLATE

FIG. 4

Table 1

Characteristics of the Apparatus Used by Bordoni

Table 1

Distance between Rod & Electrode	.1 mm
Mutual Capacity	10 pf
Frequency	7 Mc.
Driving Voltage	100 V
Length of Rod	65 mm
Diameter of Rod	12 mm
Resonant Frequency	10 - 50 KC
Typical Value of Vibration Amplitude Measured	10^{-7}cm
Output of the FM Vibration Meter for 10^{-7}cm Vibration Amplitude	40 mv.

As can be seen, very little work has been carried out using the electric method with continuous waves, and no work has been done with the electric method using a pulsed signal. For this reason and because the electric method is in many ways a better method, the work discussed in the following pages has been conducted.

II. THEORY

A. Discussion

The theory of the experiment is based on the fact that at the input of the sample acoustic waves are to be generated by the stress associated with an electric field. Here it will be shown that the stress, S, is proportional to the square of the electric field, E. We will assume a parallel plate capacitor with stationary plates. From the definition of capacitance, we can write

$$C = \frac{\varepsilon_0 A}{d} , \tag{1}$$

where A is the area of the plates, and d is their separation. Since the stress is defined as the force over an area, or

$$S = \frac{F}{A} , \tag{2}$$

and

$$F = q\, E , \tag{3}$$

we can write

$$S = \frac{qE}{A} . \tag{4}$$

Also, since

$$E = \frac{V}{d} \tag{5}$$

and

$$q = C\, V , \tag{6}$$

where V is the potential, equation (4) can be written as

$$S = \varepsilon_0 E^2 . \tag{7}$$

B. Input Electrode

The input electrode configuration consists of an electrode placed parallel to the sample and at a distance to be determined in this section. Fig. 5 shows the circuit from which this discussion is based.

From Ohm's law, we can write

$$I = V_s \; / \; [Z_s + R + i \; (\omega L - \frac{1}{\omega C})] \; , \tag{8}$$

where V_s is the source voltage, Z_s is the source impedance, and R and L form a tuning network to adjust the input signal for maximum energy transfer to the sample. C is the capacitance of the sample and electrode, which is in parallel with a variable capacitor. Setting

$$\omega L = \frac{1}{\omega C} \quad , \tag{9}$$

we have

$$LC = \frac{1}{\omega^2} \quad ; \tag{10}$$

and then

$$I = I_m = V_s / \; (Z_s + R) \; , \tag{11}$$

where I_m is the maximum current. Assuming that the source impedance is real, that is,

$$Z_s = R_s \quad , \tag{12}$$

then

$$I_m = V_s / \; (R_s + R) = V_c / \; Z_c \; , \tag{13}$$

where V_c is the voltage across the capacitor, C. Equation

Fig. 5

Circuit Diagram on Which the Input Theory is Based

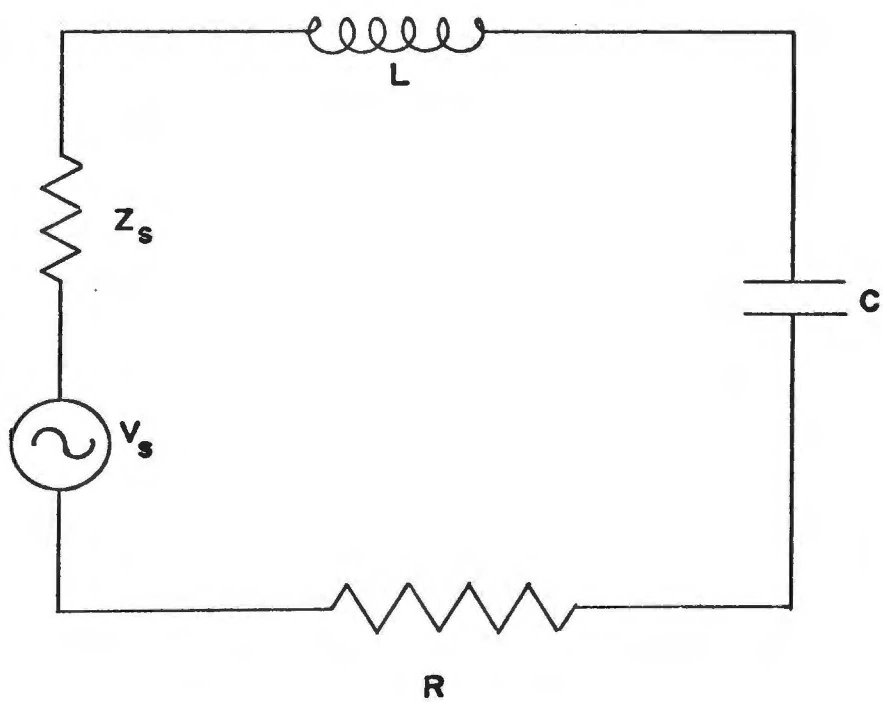

FIG. 5

(13) can be rewritten in the form

$$I_m = V_c \;/\; (-\frac{i}{\omega c}) \;, \tag{14}$$

or

$$V_c = =i[V_s/R(R_s+R)] \;/\; \omega c = -iV_{so}\; e^{i\omega t} \;/\; (R_s+R)\omega c \;, \tag{15}$$

where V_{so} is the amplitude of the source voltage, or

$$V_s = V_{so} \exp (i\omega t) \tag{16}$$

Now, by rewriting (16), we can obtain

$$V_c = -V_{co} \exp i(\omega t + \pi/2) \;, \tag{17}$$

where $i = e^{i\pi/2}$, and V_{co} is the amplitude of the voltage across the capacitor. Therefore,

$$V_{co} = V_{so} \;/\; (R_s + R)\omega C \;. \tag{18}$$

Choosing an example where R = 50 ohms, $A = 10^{-4}\ m^2$, and $d = 10^{-5}m$, then

$$C = \frac{\varepsilon_0 A}{d} = 8.85 \times 10^{-11} \text{ farad.} \tag{19}$$

Also, if V_{co} = 100 volts, and the distance between the sample and electrode is 10^{-3} cm., then

$$E_{co} = 10^5 \text{ volts/cm} \;. \tag{20}$$

Therefore, from equation (18),

$$V_{so} = 8.85 \times 10^{-7} \times 2\pi f \;. \tag{21}$$

Setting $f = 10^6$, 10×10^6, and 5×10^8, we have the results listed in Table 2. From equation (18), and because $V_{co} = E_{co}/d$, we have

Table 2

Table of Parameters Used in Equation (14)

Table 2

f, sec^{-1}	V_{so}, volts
10^6	5.55
10×10^6	55.5
100×10^6	555
5×10^8	3080

$$V_{so} = E_{co}d(R_s + R)\ \omega C = E_{co}d(R_s + R)\omega\varepsilon_0 A/d \quad , \qquad (22)$$

or

$$V_{so} = E_{co}\ (R_s + R)\omega\varepsilon_0 A \quad . \qquad (23)$$

From equation (23) we note that the required source voltage, V_{so}, does not depend on the electrode spacing, d, for a given field strength, E_{co}. It does, however, depend on the area, A, of the electrode.

C. The Detecting Electrode

The device used for the detection of the acoustical wave is essentially the same as that used for the input. The only difference is that in the detector a d.c. voltage is applied through a resistor to the capacitor, which is formed by the electrode and the sample. Fig. 6 shows the detector circuit which was used in this experiment. The output signal is detected by measuring the voltage changes across the resistor, R.

The capacitor C represents the electrode and the sample, and E is the constant d.c. voltage applied across the capacitor. If d_o represents the static spacing between the sample and electrode, and d represents the amplitude of small changes in this distance when the acoustic signal reaches the detecting end of the sample, we can write

$$C = \frac{\varepsilon_0 A}{d^1} = \frac{\varepsilon_0 A}{d_o + d \sin \omega t} \quad , \qquad (24)$$

where A is the cross sectional area of the electrode.

Fig. 6

Circuit Diagram on Which the Detector Theory is Based

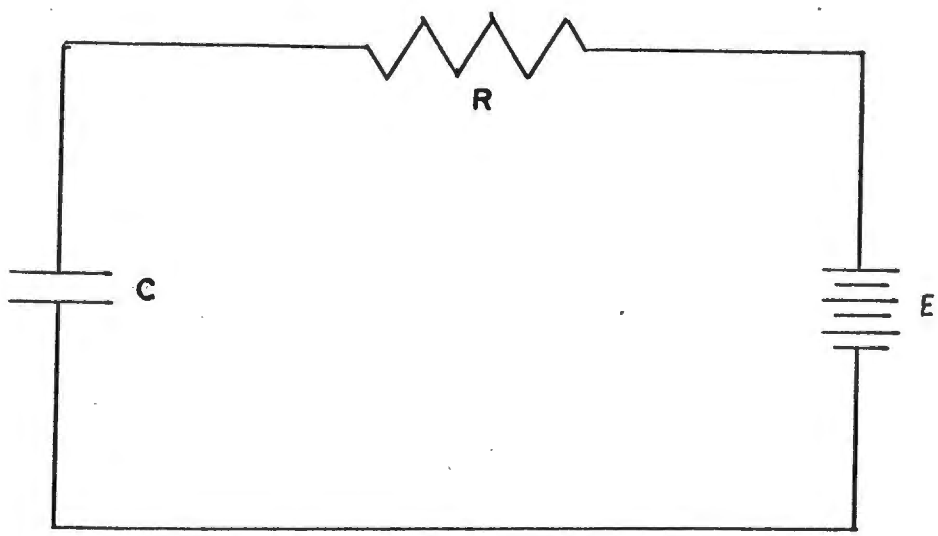

FIG. 6

By Kirchoff's law, we can write

$$E - i\,R - \frac{Q}{C} = 0 \quad , \tag{25}$$

or

$$E = R\,\frac{dQ}{dt} + Q\left[\frac{d_o}{\varepsilon_0 A} + \frac{d\,\sin\,\omega t}{\varepsilon_0 A}\right] . \tag{26}$$

By rearranging, equation (26) becomes

$$\frac{E}{R} = \frac{dQ}{dt} + Q\left[\frac{d_o}{R\varepsilon_0 A} + \frac{d\,\sin\,\omega t}{R\varepsilon_0 A}\right] . \tag{27}$$

Now, setting

$$\frac{E}{R} = P$$

$$\frac{d_o}{R\varepsilon_0 A} = D \tag{28}$$

$$\frac{d}{R\varepsilon_0 A} = F \quad ,$$

we can write

$$P = \frac{dQ}{dt} + Q\left[D + F\,\sin\,\omega t\right] \quad , \tag{29}$$

where at time $t = 0$, $Q = P/D$. Next, a solution is considered of the form

$$Q = \alpha\, e^{-\beta t} + \gamma + F\,(\,m\,\sin\,\omega t + n\,\cos\,\omega t\,). \tag{30}$$

Taking the derivative of equation (30)

$$\frac{dQ}{dt} = -\,\alpha\beta e^{-\beta t} + \omega F\,m\,\cos\,\omega t - \omega F\,n\,\sin\,\omega t \quad . \tag{31}$$

Substituting this into equation (29) gives

$$P = -\alpha\beta e^{-\beta t} + \omega F\ m \cos\omega t - \omega F\ n \sin\omega t \ .$$
$$+ \alpha D e^{-\beta t} + D\gamma + D\ F\ m \sin\omega t + D\ F\ n \cos\omega t$$
$$+ \alpha F e^{-\beta t} \sin\omega t + \gamma D \sin\omega t + F^2\ m \sin^2\omega t \quad (32)$$
$$+ F^2\ n \sin\omega t \cos\omega t$$

Combining terms with the same coefficients gives

$$-\beta + D = 0 \quad \Rightarrow \beta = D$$
$$\omega m + Dn = 0 \quad \Rightarrow n = -\frac{\omega m}{D}$$
$$-\omega\ F\ n + D\ F\ m + \gamma D = 0$$
$$\left.\begin{array}{l} F^2\ m = 0 \\ F^2\ n = 0 \end{array}\right\} \Rightarrow F = 0 \quad (33)$$
$$D\gamma = P$$
$$\alpha F = 0$$

By substituting (33) into equation (30) with $t = 0$, we get

$$m = -\ P/\omega^2 + D^2$$
$$n = \frac{\omega}{D}\ \frac{P}{\omega^2 + D^2} \quad (34)$$
$$\alpha = \frac{F\omega}{D}\ \frac{P}{\omega^2 + D^2}$$

The current i is given by

$$i = \alpha\beta e^{-\beta t} + F\ \omega m \cos\omega t - F\ \omega n \sin\omega t\ , \quad (35)$$

and the alternating current, $i(\omega)$ is

$$i(\omega) = F\ \omega(m \cos\omega t - n \sin\omega t) = F\omega(m^2 + n^2)^{\frac{1}{2}}\sin(\omega t + \phi). \quad (36)$$

From this we can find the alternating component of the voltage, $E(\omega)$, across the resistance, R:

$$E(\omega) = F\ \omega R\ (m^2 + n^2)^{\frac{1}{2}}$$
$$= F\ \omega R \frac{P}{\omega^2 + D^2} \left(1 + \frac{\omega^2}{D^2} \right)^{\frac{1}{2}}$$
$$= F\ \omega R \frac{P}{\omega^2 + D^2} \left(\frac{1}{D} \right)(D^2 + \omega^2)^{\frac{1}{2}} \tag{37}$$
$$= \frac{F\ \omega\ R\ P}{D(\omega^2+D^2)^{\frac{1}{2}}}$$
$$= \frac{d\ \omega\ E}{d_o(\omega^2+d_o^2\ /\varepsilon_0^2\ A^2R^2)^{\frac{1}{2}}}\ .$$

Considering an example where $d_o = 10^{-5}$m., $A = 10^{-4}$m^2, $R =$ 250 ohms, $\omega = 10^7$ cycles, $E = 10^2$ volts, and $d = 10^{-9}$m.,

$$D = \frac{d_o}{\varepsilon_0 AR} = 4.53 \times 10^7\ . \tag{38}$$

The R-C time constant is D^{-1}, or 2.21×10^{-7}. Therefore,

$$E(\omega) = 2.1 \times 10^{-3} \text{ volts.} \tag{39}$$

D. Frequency Doubling

The output frequency from the sample will be twice that of the input frequency because of frequency doubling at the surface of the input end of the sample. The reason is quite simple, and is as follows. The applied signal can be represented by

$$E = E_o \cos \omega t\ , \tag{40}$$

where E is the electric field and ω is the frequency. The stress at the sample surface is a function of the square of the electric field, or

$$S = \varepsilon_0 E^2 = AE_o^2 \cos^2 \omega t\ , \tag{41}$$

where A is a constant. By the relation

$$\cos 2\ \omega t = 2 \cos^2 \omega t - 1\ , \tag{42}$$

it can be shown that equation (41) becomes

$$S = AE_o^2 \; [\; \cos 2\omega t + 1] \; , \tag{43}$$

or

$$S = AE_o^2 \cos 2\omega \; t + AE_o^2 \tag{44}$$

The second term in equation (44) is a constant, and therefore contributes nothing to the time dependent stress. The first term, however, contains the variable $2\omega t$, which shows that the frequency is doubled at the surface of the input end of the sample.

E. The Output Pulse

The voltage detected at the output of the sample will be proportional to the square of the voltage at the input end. From equation (44), it was shown that at the input end, the stress was proportional to the square of the electric field intensity. Therefore, the square of the voltage at the input end will be proportional to the stress, or

$$S \propto E_i^2 \propto V_i^2 \quad . \tag{45}$$

The amplitude of the input pulse in proportional to the stress. Therefore,

$$S \propto A_i \quad . \tag{46}$$

The amplitude of the input pulse is proportional to the amplitude of the output pulse; also, the voltage of the output pulse is proportional to the amplitude of the output pulse, or

$$V_o \propto A_o \propto A_i \tag{47}$$

From equations (45) and (46), the desired result is found:

$$V_o \propto V_i^2$$

This relation will provide a future check on the results of the experiment.

III. EXPERIMENTAL PROCEDURE

A. Discussion

A block diagram of the equipment is shown in Fig. 7. The pulse generator was composed of two sections, a negative gate pulser and an oscillator, which are shown in Fig. 8. The negative gate pulse was one-half microsecond long with an amplitude of -200 volts. The oscillator had a carrier frequency between 25 and 100 megacycles. Different frequencies were generated by changing the inductance in the oscillator circuit. The sample was a single crystal of aluminum, one inch in diameter and four inches in length.

The sample holder consisted of two magnesium caps, one of which were located on each end of the sample. The caps held spring loaded electrodes which were pressed against the sample.

The output signal was detected and amplified by a General Radio model 1216-A, I.F. amplifier, connected to a Tektronix model 547 oscilloscope with a type 1A1 plug in amplifier. The following sections contain a detailed description of each of these components.

B. The Pulsed Oscillator Circuit

A pulsed oscillator is used when a waveform is desired where the pulse amplitude is zero until the beginning of the

Fig. 7

Block Diagram of Equipment Used in this Experiment

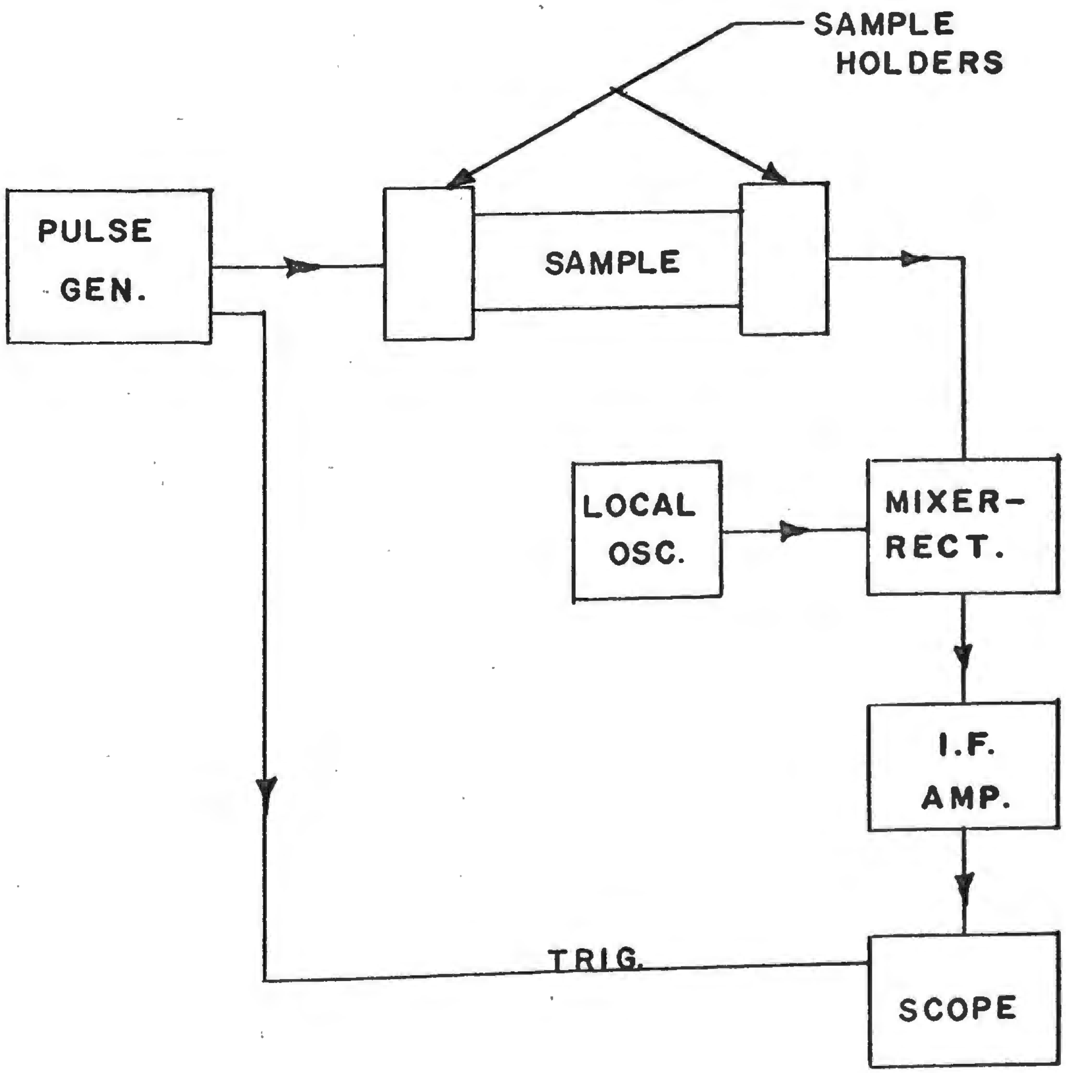
SAMPLE
HOLDERS
PULSE
GEN.
SAMPLE
LOCAL
OSC.
MIXER-
RECT.
I.F.
AMP.
TRIG.
SCOPE

FIG. 7

Fig. 8

Wiring Diagram of the Pulse Generator

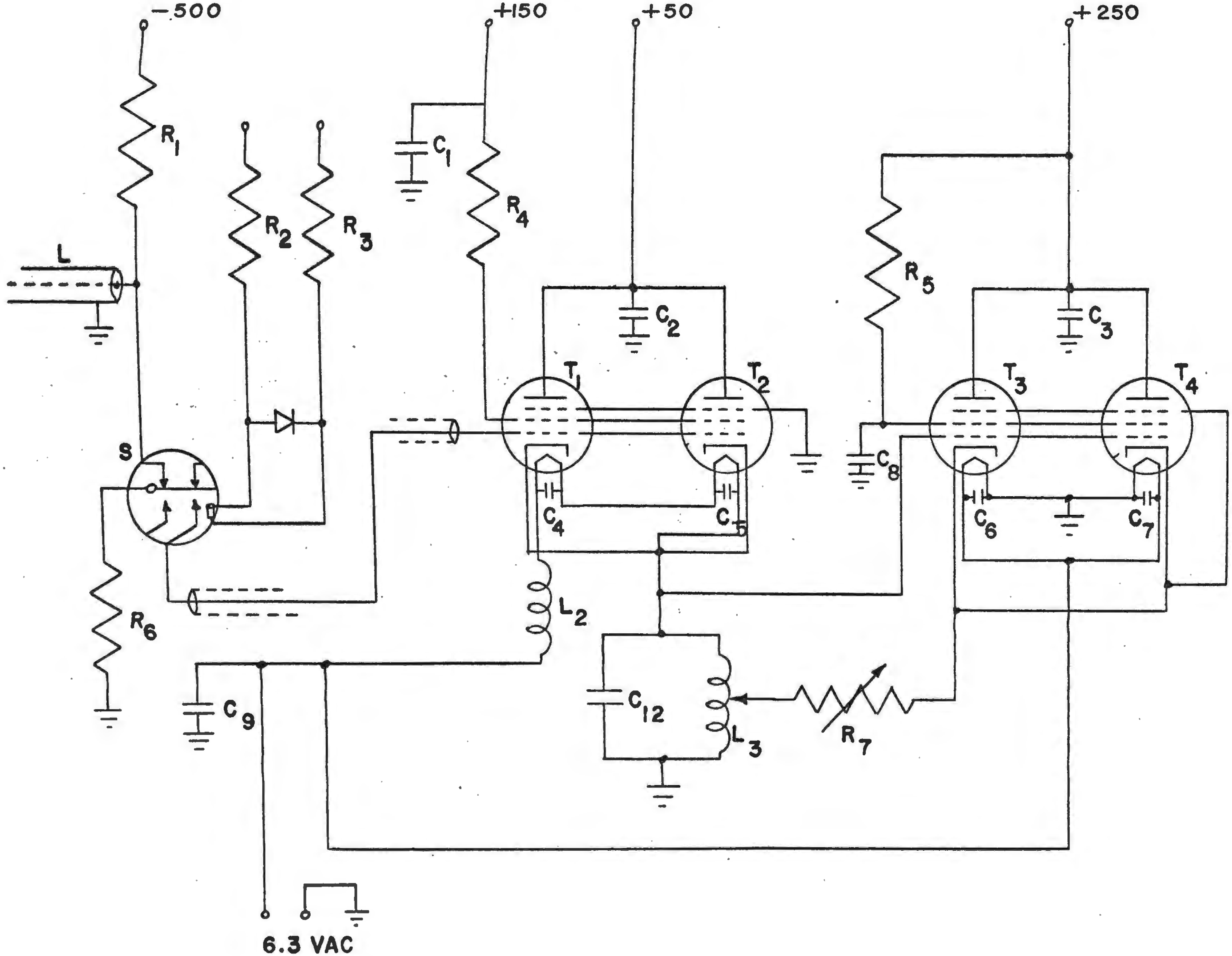
-500
+150
+50
+250
R1
R2
R3
R4
R5
R6
R7
L
L2
L3
C1
C2
C3
C4
C5
C6
C7
C8
C9
C12
S
T1
T2
T3
T4
6.3 VAC

FIG. 8

Table 3

Components Used in the Pulsed Oscillator Circuit

Table 3

R_1	100K, 1/2 watt
R_2, R_3	5.1K, 2 watt
R_4, R_5	47 ohm, 1/2 watt
R_6	90 ohm, 1/2 watt
C_1- C_7, C_9	.01µf, 1000 V. ceramic capacitors
C_{12}	Sample
T_1, T_2	6JE6A
T_3, T_4	6146B
S	Mercury Wetted Relay, HG1077, C. P. Clare & Co.
L	Delay Cable, AN Type RG 71/U
L_2	30 Turns of No. 22 Wire
L_3	4-8 Turns of No. 12 Wire
R_7	500 Ohm, Variable

pulse interval, becomes sinusoidal during this interval, and then returns to zero amplitude.

The pulsed oscillator was composed of a ringing circuit and an oscillating circuit which utilize the same tank network. The tank network is an energy storing device which is composed of a capacitor and an inductor connected in parallel. The ringing circuit and the oscillator circuit will be discussed separately. A simple ringing circuit is composed of a capacitor and an inductor placed in parallel, and connected to a voltage source through a switch. Fig. 9 shows a ringing circuit similar to the one used in this experiment, where the switch in this case is a simple triode tube. An equivalent circuit is shown in Fig. 10. Here a parallel resonant circuit is connected to a constant potential, E, through a current limiting resistor, R. The resistor, r, represents the a.c. losses in the resonant circuit. This resistor is placed in parallel to the inductor since the d.c. resistance of the inductor is small compared to the a.c. resistance, and the inductor short circuits the resistor for d.c.

Initially switch S is closed and a steady state current of E/R flows through the inductance. At the time $t = 0$, the switch is opened. The behavior of the circuit for a time greater than zero is represented by [5]

$$LrC \frac{d^2 i}{dt^2} + L \frac{di}{dt} + r\, i = 0 \quad , \tag{49}$$

where i is the current through the inductor. The solution to

Fig. 9

Ringing Circuit Similar to the One Used in This Experiment

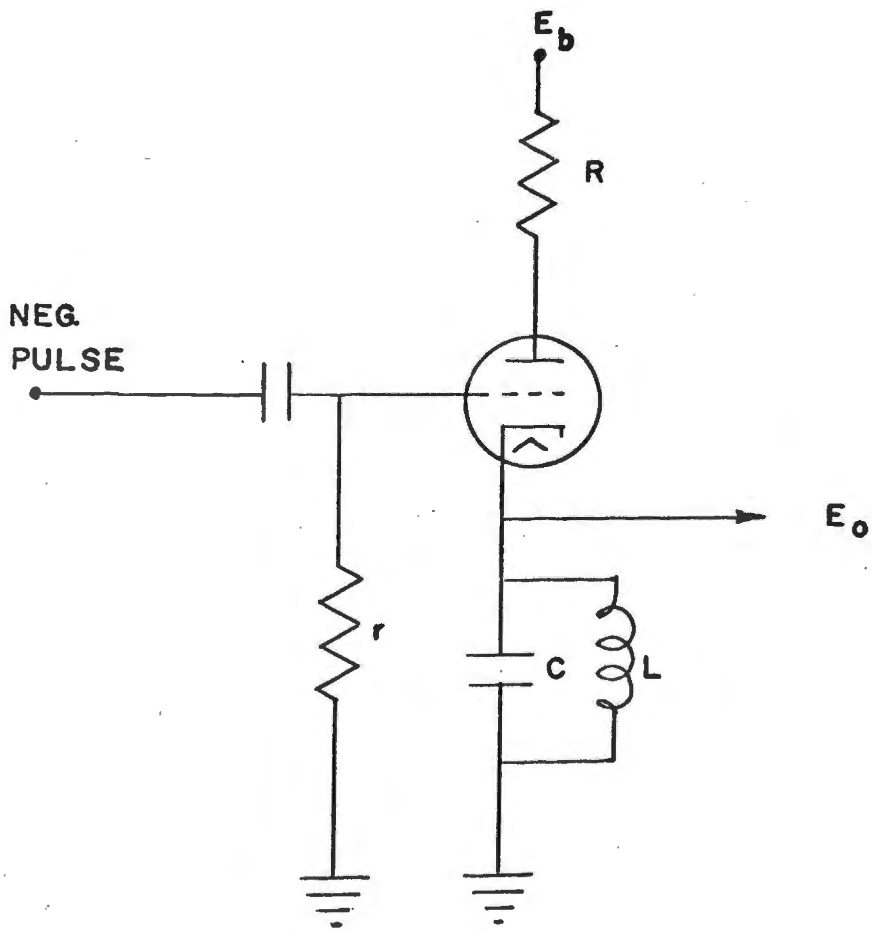

FIG. 9

Fig. 10

Equivalent Ringing Circuit

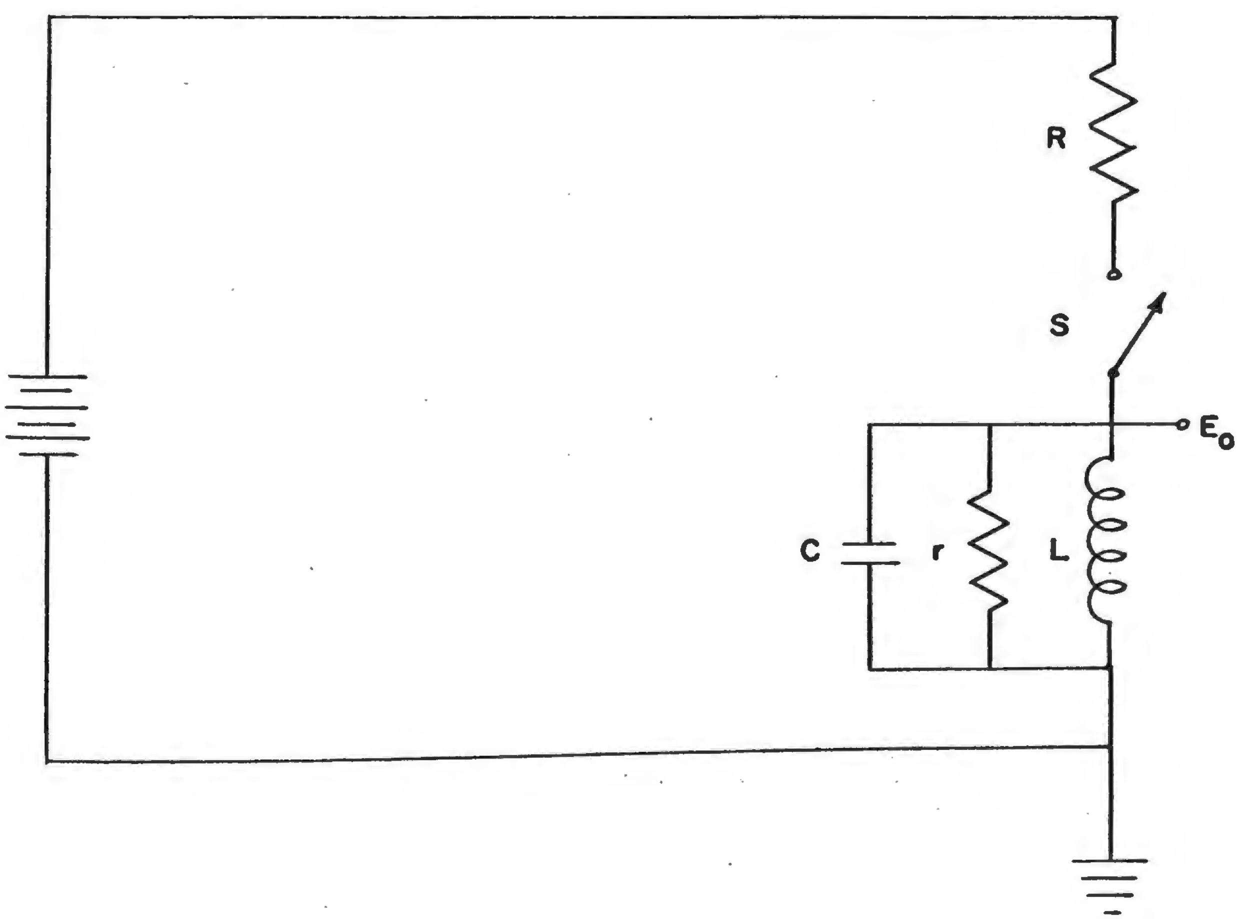

FIG. 10

(49) is given by

$$i = A\ e^{-t/2rC} \cos\ (\omega t + \phi)\ , \tag{50}$$

where

$$\omega = \left[\frac{1}{LC} - \frac{1}{4r^2c^2}\right]^{\frac{1}{2}}. \tag{51}$$

The arbitrary constants A and can be evaluated from the fact that $i = E/R$ and $di/dt = 0$, when $t = 0$. From this, we have

$$\tan\ \phi = \frac{-1}{2\ r\ c\ \omega}\ , \tag{52}$$

and

$$A = \frac{E}{R}\ [\ 1 + 1\ /\ 4r^2c^2\omega^2]^{\frac{1}{2}}\ . \tag{53}$$

The voltage E_o is expressed by

$$E_o = L\ \frac{di}{dt}\ , \tag{54}$$

and from equation (50), (54) becomes

$$E_o = -\frac{E}{R}\ [\ 1 + 1\ /\ 4r^2c^2\omega^2]\ \omega L\ e^{-t/2rc} \sin\ \omega t\ . \tag{55}$$

The quantity $rc\omega$ is called the Q of the resonant circuit. Assuming that $1/4Q^2$ is small compared to 1, equation (55) can be rewritten as

$$E_o = -\ \frac{E}{R}\ \omega L\ e^{-\omega t/2Q} \sin\ \omega t\ . \tag{56}$$

Equation (56) represents a damped sinusoidal oscillation, where the rate of damping is such that the amplitude is reduced to $1/e$ of its initial value in Q/π cycles.

The ringing of the tank circuit in Fig. 8 is initiated when the steady state current through the tubes T_1 and T_2 is suddenly shut off by the application of a negative pulse to the grids. This applied pulse must be greater than the cut-off voltage of the tube, plus the initial amplitude of the oscillations. If this is not the case, the initial amplitude of the oscillations will bring the tube back into its operating region. When the negative gate pulse returns to zero amplitude, the tube suddenly conducts and rapidly quenches the oscillations.

The ringing circuit produces a signal which is shown in Fig. 11. In order to sustain the oscillations throughout the gate pulse duration, the oscillator replaces the energy losses represented by the resistor r in Fig. 10. Fig. 12 show a simplification of the circuit which accomplishes this energy replacement. The voltage from a point A in Fig. 12 is applied to the grid of T_2, and the cathode is connected through a resistor, R_1, to a tap on the inductance. In practice, the gain of this network may be greater or less than unity. The gain can be made to be unity by adjusting the variable resistor, R_1, thus yielding pulses of constant amplitude. If tube T_2 were omitted, the voltage across the tank circuit would have an initial amplitude of $I_o \omega L$, where I_o is the initial current in the tank circuit. If the feedback from T_2 is adjusted to the value required to supply the tank circuit losses, the amplitude of the signal will remain at $I_o \omega L$.

The resistor R_1 is used to adjust the amount of feedback

Fig. 11

Photograph of the Ringing Circuit Output

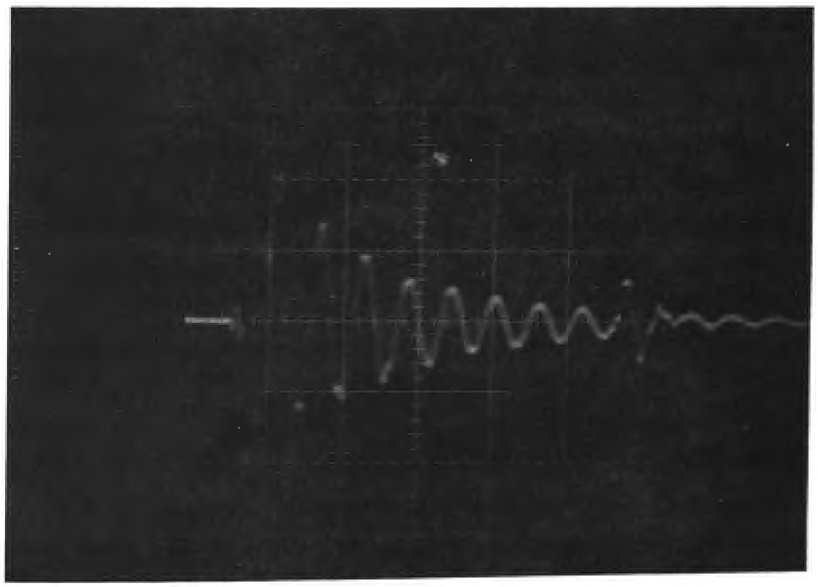

FIG. 11

Fig. 12

Feedback Oscillator

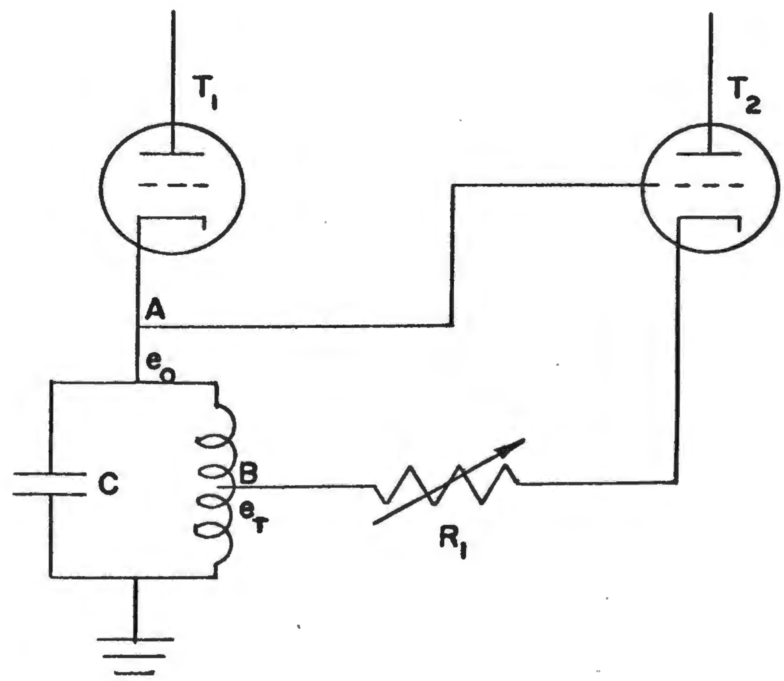

FIG. 12

to the tank circuit. An approximate value of R_1 is easily calculated. First assume that the loop gain of the system in Fig. 12 is unity; also assume that the inductor is tapped at its midpoint. The impedance, R_T, looking into the center tap is 1/4 ωLQ. Since the tank voltage, e_o, equals $2e_T$, then for the loop gain to be unity, the ratio e_o/e_T must equal 2. Therefore,

$$\frac{R_T}{(R_1 + R_T)} = 1/2 \quad , \tag{57}$$

or

$$R_1 = R_T = 1/4\ \omega LQ \quad , \tag{58}$$

which was verified in practice. Fig. 13 shows a photograph of the pulse taken directly across the tank circuit.

C. The Pulser Circuit

In order to turn off the tube T_1 in Fig. 12, a negative gate pulse must be applied to its grid. The amplitude of this pulse must be greater than the cut-off voltage of the tube, plus the initial amplitude of the ringing sinusoidal wave from the tank circuit. For this reason a negative gate pulse of approximately 200 volts amplitude was needed. To produce this pulse a delay line and switching network was used, which is shown in Fig. 14.

Essentially, the pulser consists of a source of d.c. voltage, a switch, and a length of coaxial cable which is terminated by an open circuit at the far end.[6] Referring to Fig. 14, S is a relay with mercury wetted contacts, and

Fig. 13

Photograph of the Output of the Pulsed Oscillator

Sweep: .1 μ sec/cm

Vertical: 50 V/cm

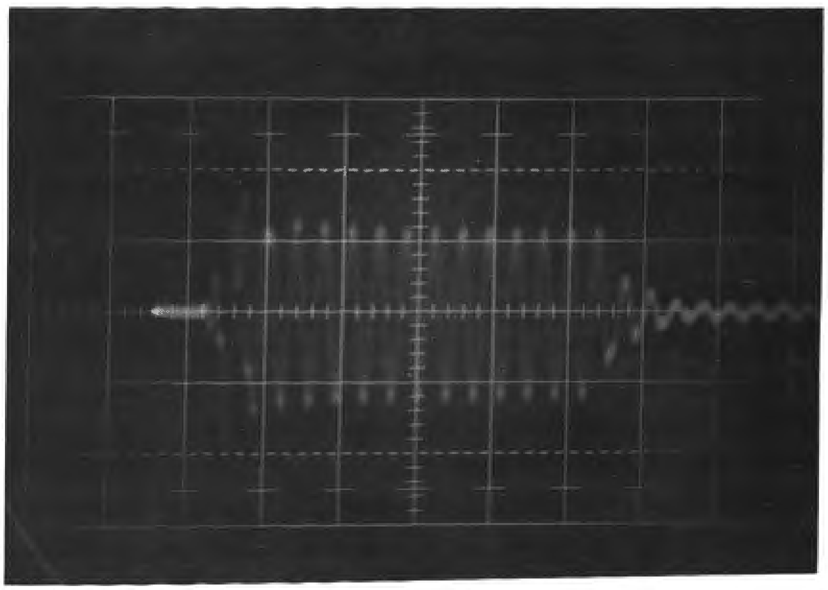

FIG. 13

Fig. 14

Circuit Used to Produce the Negative Gate Pulse

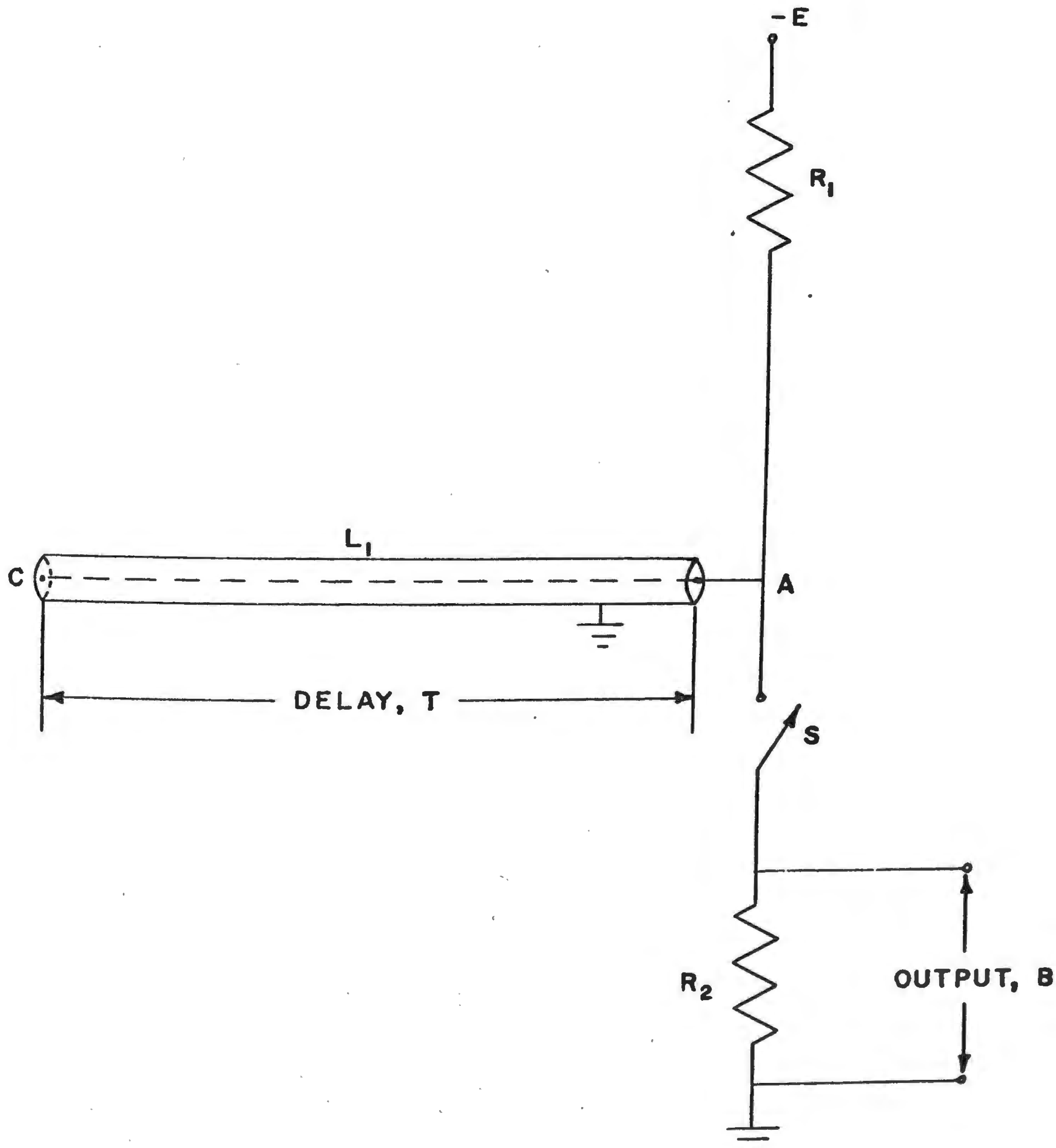

FIG. 14

driven by 60 cycle line voltage. The pulse forming coaxial cable is represented by L .

Fig. 15 shows the wave forms during one cycle of operation. Between pulses, L_1 is charged to a potential of -E through the high resistance, R_1. At the time t_1 the switch closes, and the line (which may be considered as a generator of potential -E and internal impedance of 90 ohms) is discharged by the 90 ohm terminating resistor R_2. Since the impedance of L_1 is equal to R_2, the potential at A increases from -E to -E/2, and that of B falls from zero to -E/2. This transient occurs very rapidly and is slowed only by stray capacitances. The voltage step -E/2 travels down L_1 taking time T to do so. The line is open at the far end, and hence the reflections occur without inversion. At the time t_3, which is twice the delay time of L_1, the waveform step at B is cancelled, making a pulse duration twice the delay time of L_1 and of amplitude -E/2. At the time t_4, S opens, allowing L_1 to charge exponentially to a potential of -E.

D. The Sample Holder

The sample holder was composed of the input and detecting electrodes which were located at each end of the sample. A cross-sectional view of the device that holds the electrode in place is shown in Fig. 16. The sample was placed in a plastic insert which insulated the sample from the metal base. The electrode was made of bronze, ground flat on one face.

Fig. 15

Waveforms Found at Various Points in Fig. 14

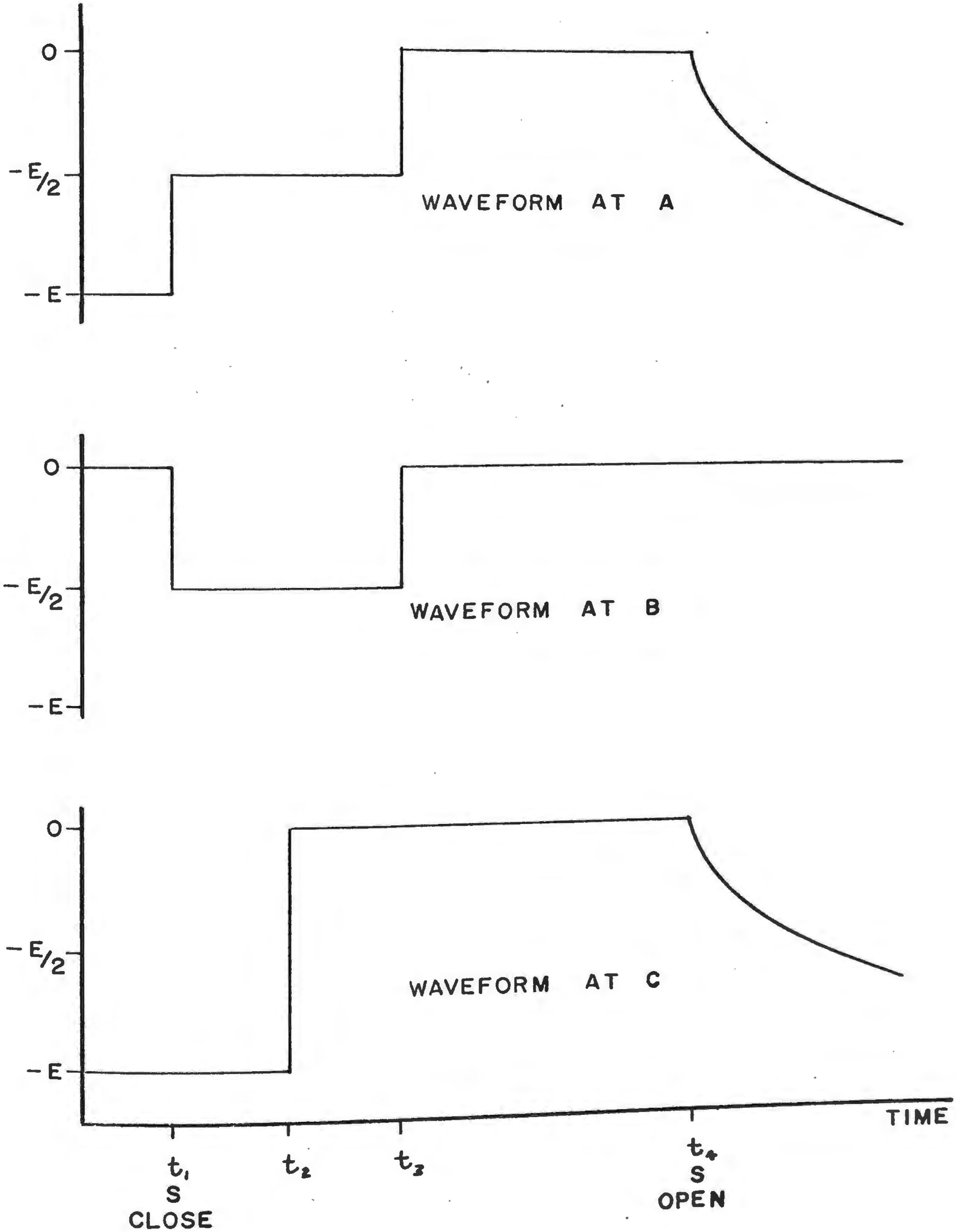
0
-E/2
-E
WAVEFORM AT A
0
-E/2
-E
WAVEFORM AT B
0
-E/2
-E
WAVEFORM AT C
TIME
t_1
S
CLOSE
t_2
t_3
t_4
S
OPEN

FIG. 15

Fig. 16

Sample Holder

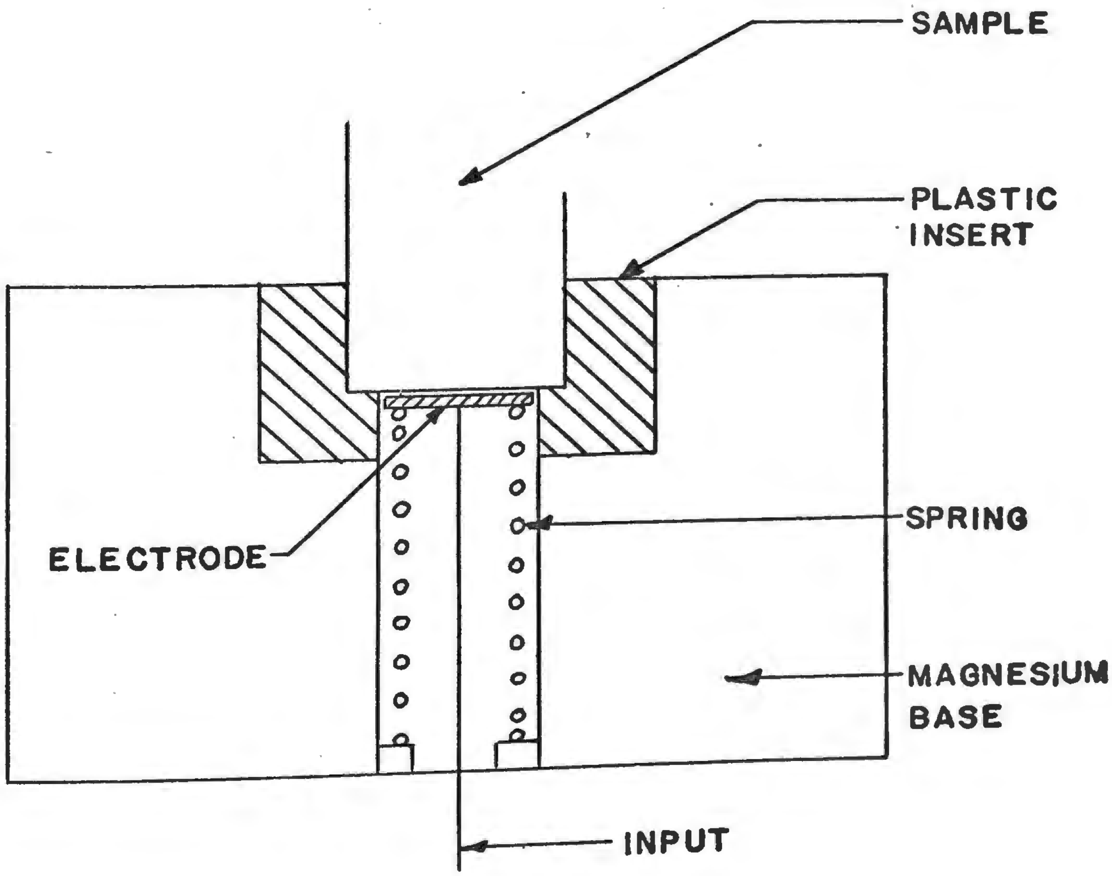
SAMPLE
PLASTIC INSERT
ELECTRODE
SPRING
MAGNESIUM BASE
INPUT

FIG. 16

This electrode was fitted into an expansion spring which forced the electrode against the sample. The electrode was kept away from the sample by three small plastic spacers, each three mils in thickness. Since the input signal was of the order of 100 volts peak to peak, the sample, with its holders, was placed in a vacuum so that the area near the electrode was free from any gas which could have caused electrical breakdown. The sample was held at ground potential while the signal was impressed on the electrodes. The detecting electrode was of the same design as the input electrode except that the detector was biased with 100 volts d.c. in series with a small resistor. This circuit is shown in Fig. 17. The I.F. amplifier was connected across this resistor, and the rectified signal from the amplifier was observed on an oscilloscope.

Fig. 17

Dectecting Circuit

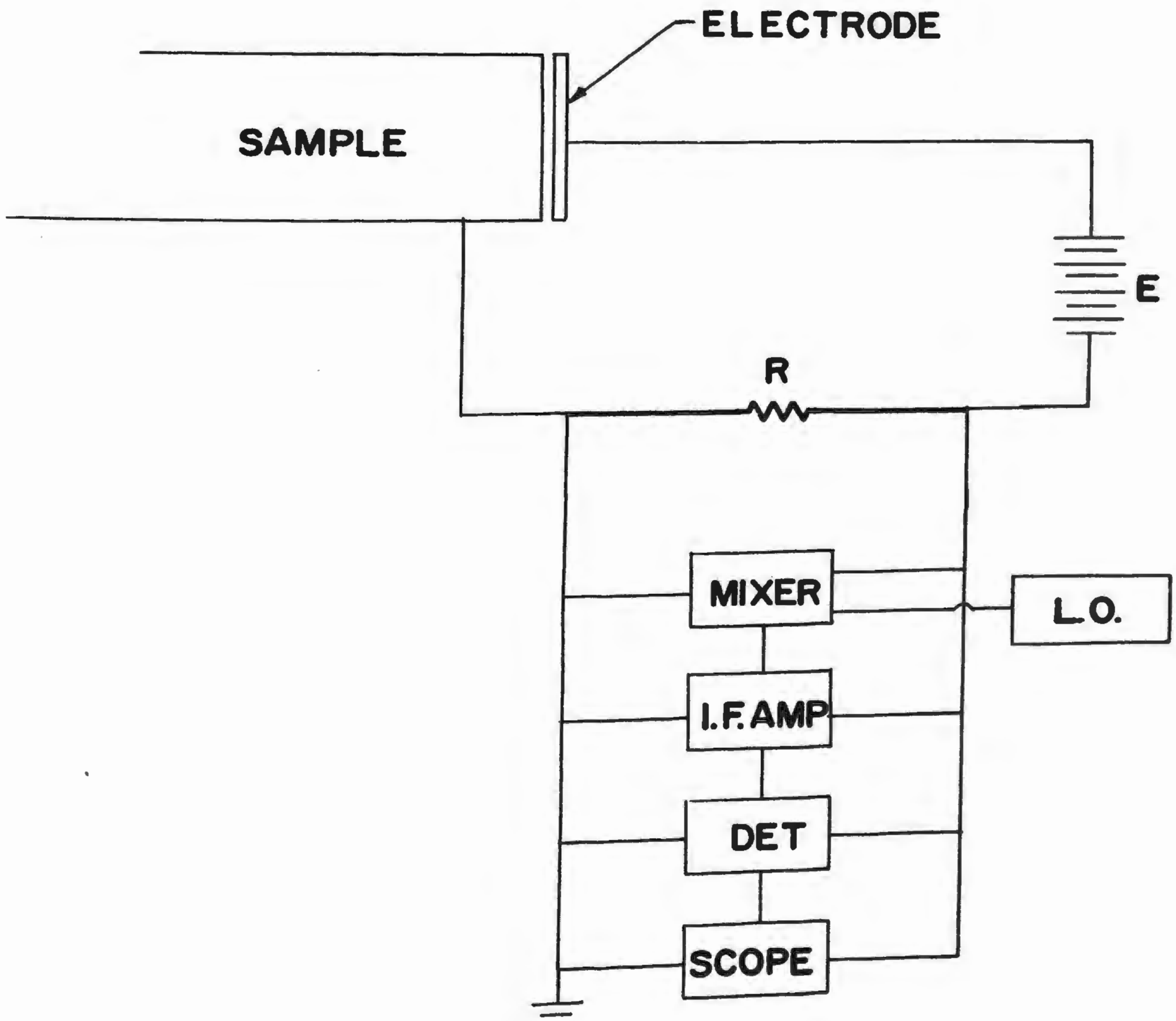

FIG. 17

IV. RESULTS AND CONCLUSIONS

The photograph in Fig. 13 shows the 25 megacycle pulse which was impressed on the input end of the sample. The signal from the output of the sample was mixed with the output of a local oscillator. When the local oscillator frequency was 80 megacycles, the d.c. level meter on the I.F. amplifier was at a maximum. This shows that a 50 megacycle signal was being detected from the sample output, and that the input frequency was, in fact, being doubled. Fig. 18 is a photograph of the detected pulse.

Two other checks were made to insure the observed frequency was originating at the sample output. First, the input and output signals were observed simultaneously on the scope, as shown in Fig. 19. Fig. 20 shows the delay to be 16 microseconds. The calculations in Appendix II show this is the delay time to be expected. Secondly, from equation (48), the output voltage is proportional to the square of the input voltage. Fig. 21 shows the behavior of the output voltage as the input signal was attenuated; as is observed, the graph is nearly of quadratic form.

The results given above show that the electric method is capable of generating pulsed ultrasonic waves in solids. In addition, it has been shown that these ultrasonic waves are detectable using a biased, capacitive pickup transducer.

Fig. 18

Photograph of the Detected Pulse

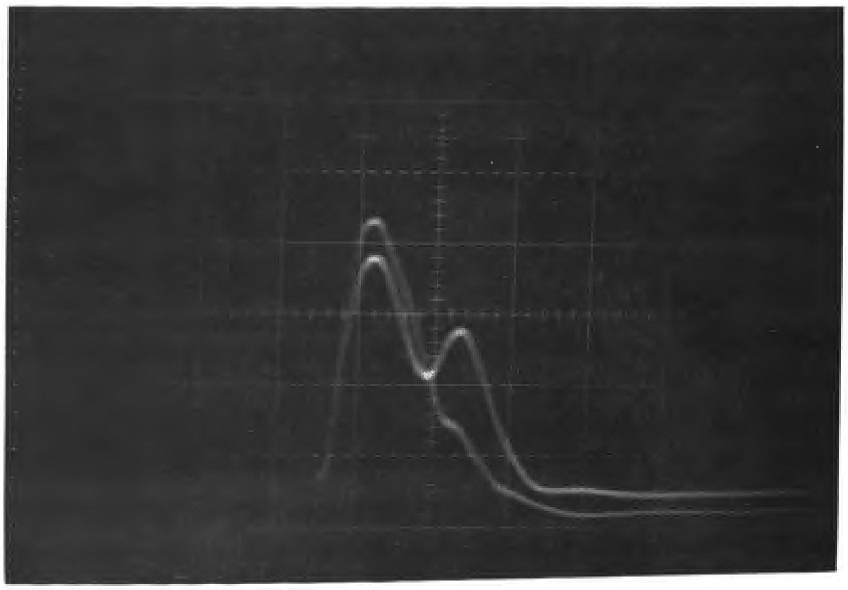

FIG. 18

Fig. 19

Time Delay Circuit

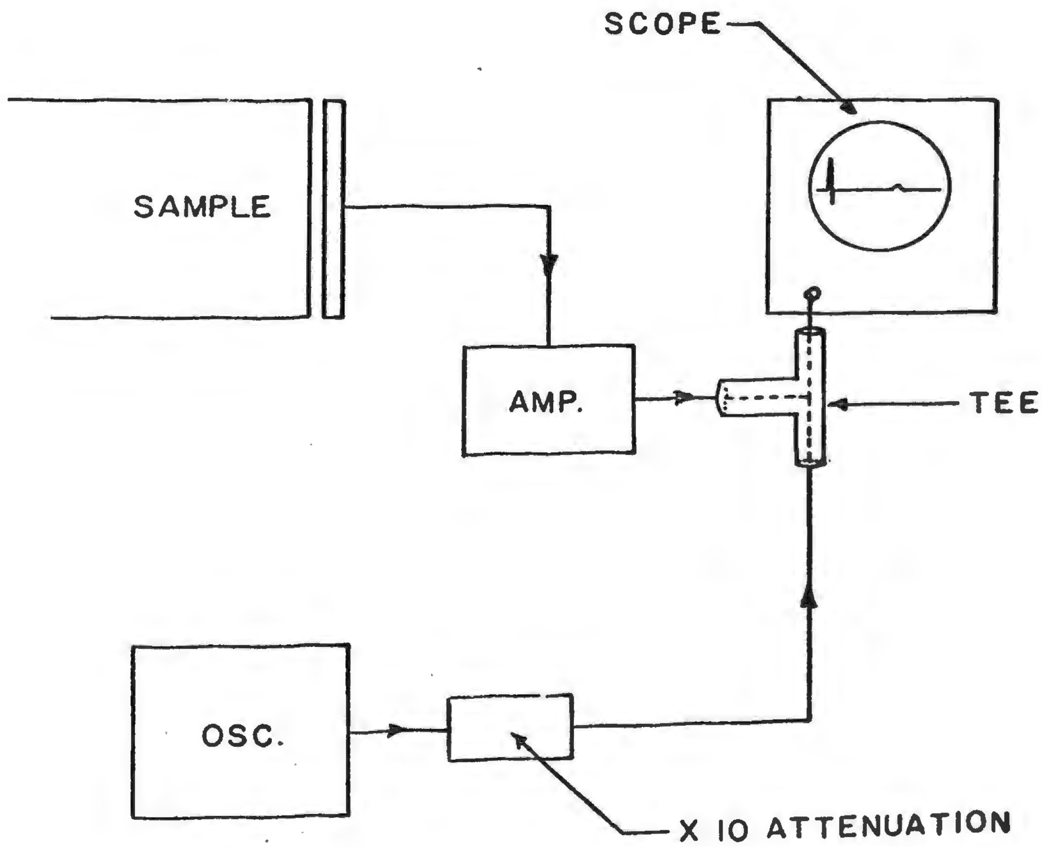

FIG. 19

Fig. 20

Photograph of the Delayed Output Pulse Relative to the Input Pulse

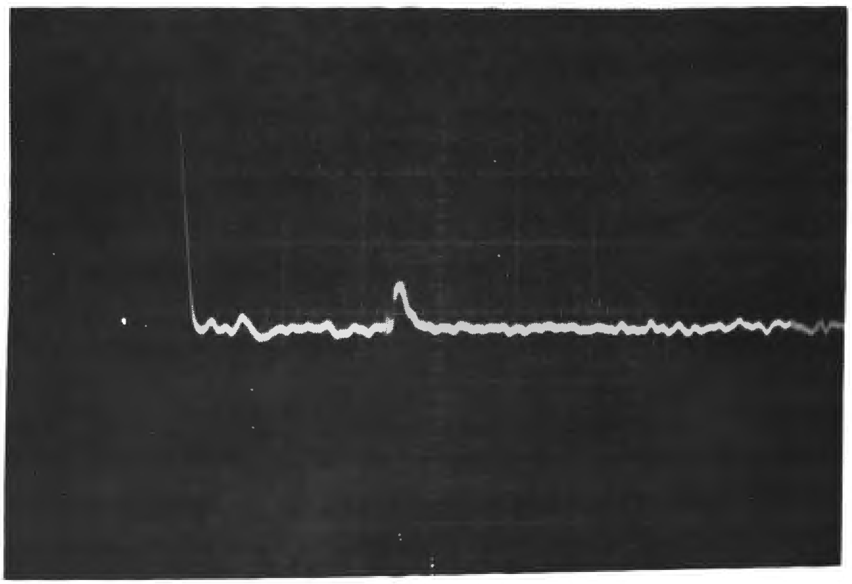

FIG. 20

Fig. 21

Graph of the Input Voltage v.s. the Detected Voltage

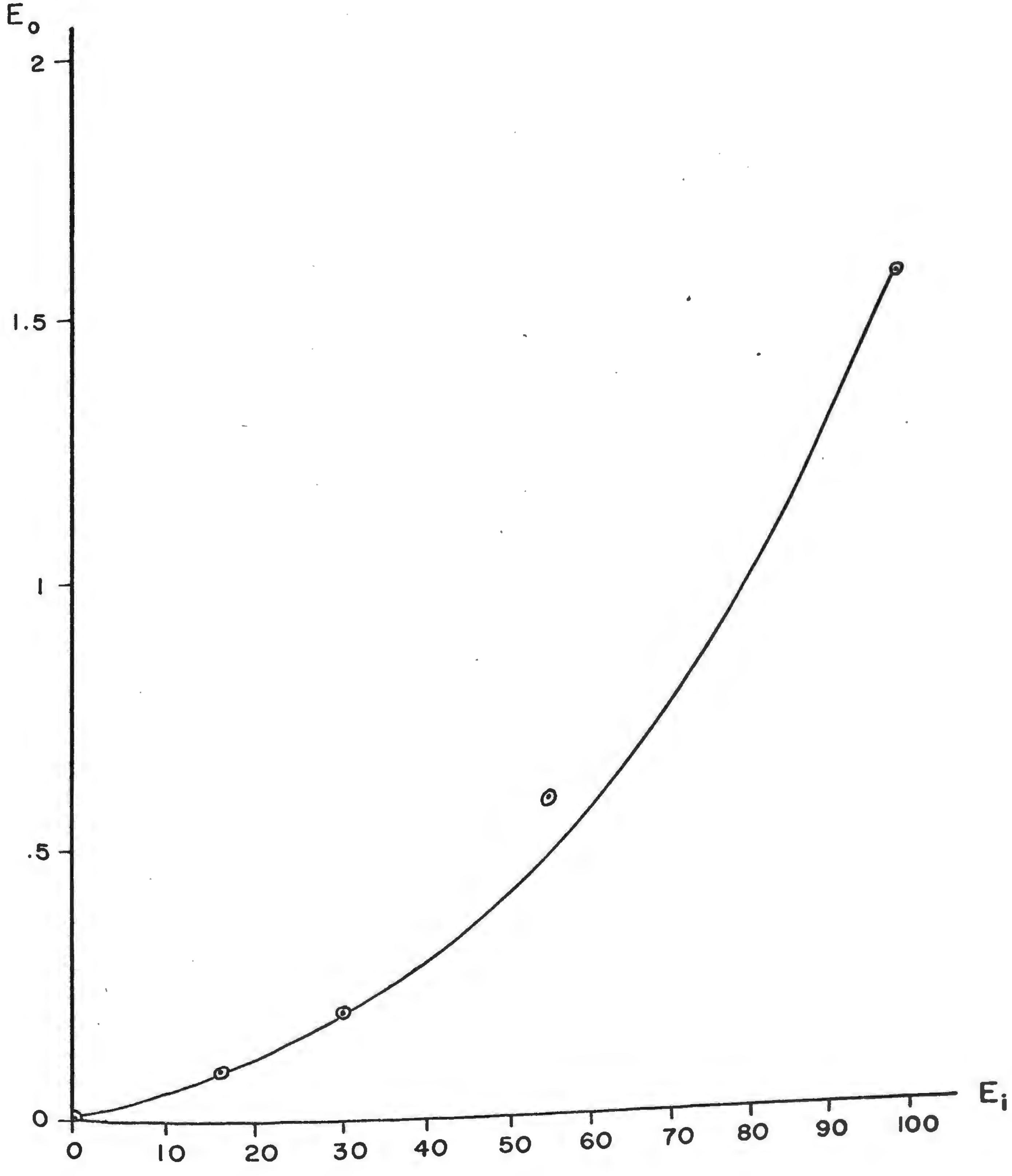

FIG. 21

With improvements such as filtering the noise in the output circuit, useful research utilizing these electrical techniques is possible.

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APPENDIX I

List of Equipment

APPENDIX I

General Radio Type 1216-A Unit I.F. Amplifier

General Radio Type 874-MR Crystal Mixer

General Radio Type 1215-C Unit Oscillator

General Radio Type 1211-C Unit Oscillator

Tektronix Type 547 Oscilloscope

Tektronix Type 1A1 Dual Trace Plug in Unit

APPENDIX II

Time Delay of the Pulse in the Sample

APPENDIX II

For a sample grown in the [110] direction, we have

$$\omega^2\rho = 1/2\ (C_{11} + C_{12} + 2C_{44})\ K^2 , \tag{59}$$

where ω is the frequency, ρ is the density, C_{ij} is the stiffness constant, and K is the wave number, or ω/V. Therefore,

$$\omega^2\rho = 1/2\ (C_{11} + C_{12} + 2C_{44})\omega^2/V \tag{60}$$

and

$$V = \left(\frac{C_{11} + C_{12} + 2C_{44}}{2\ \rho}\right)^{\frac{1}{2}}. \tag{61}$$

Since

$$\begin{aligned} C_{11} &= 1.068 \times 10^{12}\ \text{dynes/cm}^2 \\ C_{12} &= .607 \times 10^{12}\ \text{dynes/cm}^2 \\ C_{44} &= .282 \times 10^{12}\ \text{dynes/cm}^2 \\ \rho &= 2.733\ \text{grams/cm}^3 , \end{aligned} \tag{62}$$

we have,

$$V = 6.4 \times 10^5\ \text{cm/sec} . \tag{63}$$

Therefore, since the time delay is given by

$$T = \chi/V , \tag{64}$$

where χ is the length of the sample,

$$T = 15.9\ \text{microseconds} . \tag{65}$$

VITA

The author was born on January 3, 1942 at Palo Alto, California. He received his primary and secondary education at Philadelphia, Pennsylvania, and at Concord, New Hampshire. In the fall of 1960 he entered the University of New Hampshire, and received a B.S. degree in Physics in June, 1965. In September, 1965, he entered the Graduate School of the University of Missouri at Rolla.